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MODELLING THE *IRAS* COLORS OF GALAXIES

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ABSTRACT: A physical interpretation is proposed for the color-color diagram of galaxies which are powered only by star formation. The colors of each galaxy result from the combination of two components: cirrus-like emission from the neutral disk, and warmer emission from regions directly involved in on-going star formation. This approach to modelling the emission is based on dust properties, but independent evidence for it is found in the relation between the color sequence and the luminosity sequence. Implications of data and interpretation are discussed and possible tests mentioned for the model.

1. INTRODUCTION

While still unfolding, the contribution of *IRAS* to extragalactic astronomy has already attained remarkable proportions. Perhaps the most dramatic quantitative expression of this contribution has been the staggering increase in the number of objects accessible to study: from fewer than a hundred in the pre-*IRAS* era to about 20,000 detections in the Point Source Catalog (Helou 1986a), and the promise of at least another 10,000 sources at the completion of the Faint Source Survey (which will average the individual detector output from all survey scans before searching for detections). Even though the spectral coverage of *IRAS* is limited to four bands (12, 25, 60 and 100 μm), and most galaxies are detected in only two of these bands (60 and 100 μm), it is the large number of objects that both demands *and* makes possible a detailed interpretation of the origin of the infrared flux. The starting hypothesis, predating *IRAS* (Wynn-Williams 1982), that needs improvement is that far-infrared emission is proportional to the rate of formation of massive young stars in the system. Rowan-Robinson (in this volume, hereafter RR) reviews several attempts at an improved interpretation, all of which try to decompose a galaxy's *IRAS* emission into physically distinct components.

The present contribution summarizes (§2) the model presented in Helou 1986b (hereafter H86), and addresses in some detail (§3) two specific aspects of that model, namely the assumption of small optical depths in the infrared, and luminosity constraints on the model. Implications and tests are reviewed briefly in §4. In what follows objects whose emission is dominated or affected by a Seyfert or quasar-like nucleus are excluded from the discussion, so the mid- and far-infrared emission from all systems considered is mostly due to thermal radiation from interstellar dust grains heated by starlight.

2. MODEL SUMMARY

A scatter diagram of $R(60/100)=f_\nu(60\mu m)/f_\nu(100\mu m)$ *vs* $R(12/25)=f_\nu(12\mu m)/f_\nu(25\mu m)$ shows "normal galaxies" spreading out along a band such that R(12/25) and R(60/100) are *anti-correlated* (Figure 1 of H86 or Figure 9 of RR). While R(12/25) increases along the band, apparently signalling hotter dust, R(60/100) decreases, signalling cooler dust! The resolution to this paradox is found in the properties of the dust rather than in those of the galaxies.

In part as a result of the *IRAS* data, it is now recognized that realistic models of interstellar dust must include a population of very small grains (Beichman 1987), extending the size distribution into the range of polycyclic aromatic hydrocarbons, *i.e.* a few Å. As such a mixture of dust is heated by increasingly intense radiation fields (Désert 1986), the *IRAS* colors of its emission trace out a curve like the one labelled D in Figure 2 of H86, or Figure 9 of RR. The shape of that curve is dictated by the presence of very small grains and by the emission features of polycyclic aromatic hydrocarbons at 7.7, 8.6 and 11.3 μm (Puget, Léger and Boulanger 1985), and reflects in particular the transition from the dominance of temperature fluctuations at low intensity of heating flux (Draine and Anderson 1985) to dominance by single temperature emission from grains in equilibrium at high intensity. As can be seen in Désert (1986), the smallest grains transiently heated to very high temperatures emit with a spectrum extending down to a few μm, and with an intensity scaling roughly linearly with the intensity of heating radiation. This emission dominates at low heating intensities, i.e. for cirrus, at the lower end of curve D. As the heating increases, larger grains reach higher equilibrium temperatures, and their blackbody spectrum starts moving into the *IRAS* bands, until it dominates and determines the colors at the uppper end of curve D.

Since the emission from any galaxy is a mixture of components all of which lie on curve D, galaxies are expected to fill out a region of the color-color plane whose upper envelope is the "heating curve" D. Rather than assume arbitrary mixing between any number of points on the heating curve to generate galaxy colors, H86 proposes a simple model with two components: (1) $\mathcal{C}(\nu)$, cirrus-like emission whose colors are constant from one galaxy to the next, typified by emission from the neutral interstellar medium in the solar neighbourhood, and (2) $A(\nu)$, emission directly associated with active star formation, especially from dust within HII regions and their immediate surroundings, such as outer layers of molecular clouds. This second component $A(\nu)$ is assumed to have variable colors: if the galaxy is forming stars mostly in high density regions, the dust exposed to high heating intensities will place $A(\nu)$ at the upper left hand side of curve D. If on the other hand the majority of HII regions in a galaxy are mature, extended low density objects, then the colors of the active component will place it lower on that curve. Thus the model relates the infrared colors of a galaxy to two physical parameters, the ratio between active region and cirrus emission, and the effective gas density in regions of active star formation.

3. MODEL DISCUSSION

The heating curve D is of course a function of properties and size distribution of the dust grains, which is a serious limitation to the accuracy to which it can be specified. Its over-all character however is quite unlikely to change. A basic assumption in using Désert's (1986) calculations is that optical depths *in the infrared* are never large enough over so large a fraction of the emitting medium that infrared colors are affected. Burstein and Lebofsky (1986) have found evidence suggesting that the disks of galaxies are optically thick in the infrared, but Persson, Rice and Bothun (1987) show data suggesting otherwise. The assumption that most galaxies are optically thin in the infrared is supported in the Milky Way, where the 12 μm extinction in the direction of the Galactic center is only about one magnitude, low enough to allow detection of 12 μm sources in the Galactic nucleus and beyond, without any patchiness in their projected distribution (Habing *et al.* 1985). That assumption should therefore hold in a galaxy whose interstellar medium mass is less than a few times the corresponding mass in the Milky Way. It may break

down in a few cases, namely those with very massive *and* dense concentrations of gas and dust, e.g. systems containing mega-masers (Baan and Haschick 1984).

In defining the components in this model, the approach is phenomenological in essence. There are clearly many possible choices for emission components (see RR), and no obvious way to decide where to place them in the color-color diagram in the absence of "perfect" dust models. One additional constraint however results from the luminosity sequence associated with the galaxy distribution in the color-color diagram. Total infrared luminosity and especially infrared to blue ratio increase substantially from the lower right hand end to the upper left hand end of the galaxy band. For instance, in the sample used in H86 the median value of $f_\nu(25\mu m)/D^2$ (where D in the optical diameter of the galaxy) increases by almost an order of magnitude when R(60/100) goes from 0.37 to 0.65. This trend can become a constraint on the emission models: Suppose a galaxy's spectrum is being synthesized by adding to the cirrus spectrum (component *C*) a gradually increasing contribution from a component *A* whose colors place it above and to the left of the observed galaxy band. Then the associated increase in the amplitude of the synthesized spectrum can be interpreted as the luminosity trend and constrained to be of the appropriate amount to agree with the observations. It turns out that the large increase in infrared luminosity (scaled to the size of the system) from one end of the band to the other forces a choice of components whose colors fall basically at the boundary of the galaxy distribution. This argument for the general placement of curve D is completely independent of the curve's physical justification above.

4. IMPLICATIONS

The most significant implication of the observed color-color diagram is in demonstrating that emission from some galaxies is dominated by cirrus, and from others by recent star formation. The model proposed in H86 quantifies the relation between far infrared emission and the recent star formation rate in a galaxy, with the unavoidable conclusion that the number of young stars in a galaxy is not simply proportional to the infrared luminosity. This proportionality holds for many galaxies (*e.g.* star-burst objects), but fails by uncertain and varying amounts for the others. Other implications of the model can be used as potential tests:

(i) In the *IRAS* color-color diagram, the model expects the colors of HII regions to place them near curve D. Unfortunately, the relevant data are not yet available, mostly because of difficulties in extracting HII regions in the *IRAS* data from the surrounding background (Pérault 1986).

(ii) Another prediction is that the active component should correlate with tracers of recent star formation such as thermal radio or Hα emission, and should do so better than the total infrared emission. A first investigation (Persson and Helou 1987) has shown encouraging results, even though using a more rudimentary model which keeps the colors of both active and cirrus components fixed.

(iii) An indirect test related to selection effects is suggested by the fact that for any reasonable choice of curve D, the model expects more galaxies to appear just below the band which is now filled out. Since the galaxies shown on the color-color diagram were chosen to be detected in four bands *and* unresolved by *IRAS*, they are biassed towards high infrared luminosity and high surface brightness. Optically selected galaxy samples may provide indirect confirmation for the model if they tend to fill the area just below the band in the color-color plane.

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